Research Councils UK Energy Programme Strategy Fellowship

Summary of Workshop on

Fossil Fuels and Carbon Capture and Storage

Working Document

March 2013

This is a report of a Workshop held to support the development of the Research Councils UK Energy Research and Training Prospectus at John McIntyre Conference Centre, Pollock Halls, Edinburgh on 8-9 January 2013

Dr Matthew Hannon
Dr Aidan Rhodes
Prof Jim Skea
Centre for Environmental Policy
Imperial College London
14 Princes Gardens
London SW7 1NA
http://www3.imperial.ac.uk/icept/ourresearchactivities/rcukenergyprogramme

Research Councils Energy Programme

The Research Councils UK (RCUK) Energy Programme aims to position the UK to meet its energy and environmental targets and policy goals through world-class research and training. The Energy Programme is investing more than £625 million in research and skills to pioneer a low carbon future. This builds on an investment of £839 million over the period 2004-11.

Led by the Engineering and Physical Sciences Research Council (EPSRC), the Energy Programme brings together the work of EPSRC and that of the Biotechnology and Biological Sciences Research Council (BBSRC), the Economic and Social Research Council (ESRC), the Natural Environment Research Council (NERC), and the Science and Technology Facilities Council (STFC).

In 2010, the EPSRC organised a Review of Energy on behalf of Research Councils UK in conjunction with the learned societies. The aim of the review, which was carried out by a panel of international experts, was to provide an independent assessment of the quality and impact of the UK programme. The Review Panel concluded that interesting, leading edge and world class research was being conducted in almost all areas while suggesting mechanisms for strengthening impact in terms of economic benefit, industry development and quality of life.

Energy Strategy Fellowship

The RCUK Energy Strategy Fellowship was established by EPSRC on behalf of Research Councils UK in April 2012 in response to the international Review Panel's recommendation that a fully integrated "roadmap" for UK research targets should be completed and maintained. The position is held by Jim Skea, Professor of Sustainable Energy in the Centre for Environmental Policy at Imperial College London. The main initial task is to synthesise an Energy Research Prospectus to explore research, skills and training needs across the energy landscape. Professor Skea leads a small team at Imperial College London tasked with developing the Prospectus.

The Prospectus will contribute to the evidence base upon which the RCUK Energy Programme can plan forward its activities alongside Government, RD&D funding bodies, the private sector and other stakeholders. The tool will highlight links along the innovation chain from basic science through to commercialisation. The tool will be flexible and adaptable and will take explicit account of uncertainties so that it can remain robust against emerging evidence about research achievements and policy priorities.

One of the main inputs to the Prospectus is a series of four high-level strategic workshops and six in-depth expert workshops taking place October 2012- July 2013. Following peer-review, the first version of the Prospectus will be published in November 2013 and will then be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This document reports views expressed at an expert workshop held in January 2013. These views do not necessarily represent a consensus of workshop participants nor will they necessarily be endorsed in the final version of the Energy Research and Training Prospectus.

Contents

List of Acronyms

BECCS	Biomass with CCS
CBM	Coal bed methane
CCS	Carbon capture & storage
CDR	Carbon dioxide removal
CDT	Centre for Doctoral Training
CPD	Continuing professional development
DAC	Direct Air Capture
DECC	Department of Energy & Climate Change
EOR	Enhanced oil recovery
EPSRC	Engineering & Physical Sciences Research Council
ETI	Energy Technologies Institute
HCV	Higher calorific value (gas)
IEA	International Energy Agency
MOF	Metal organic framework
NERC	Natural Environment Research Council
OSPAR	OSPAR Convention guides international cooperation on the protection of the marine environment of the North-East Atlantic.
RAMO	Reliability, availability, maintainability and operability
RCUK	Research Councils UK
PESTEL	Political, Economic, Social, Technological, Environmental, Legal
RD&D	Research Development & Deployment
TRL	Technology Readiness Level
TSB	Technology Strategy Board
UCG	Underground coal gasification
US DOE	United States Department of Energy

1 Introduction to workshop

This document summarises the outcomes of a workshop held on 8-9 January 2013 in order to identify research and training needs that might be taken forward by Research Councils UK in the fields of fossil fuels and carbon capture and storage (CCS). In terms of scope, the workshop covered the follow areas defined under the EU/International Energy Agency (IEA) energy R&D nomenclature:

- Enhanced oil and gas production
- Refining, transport and storage of oil and gas
- Non-conventional oil and gas production
- Oil and gas combustion
- Oil and gas conversion
- Other oil and gas
- Coal production, preparation and transport
- Coal conversion
- Other coal
- CO_2 capture/separation
- CO_2 transport
- CO_2 storage

Given the number of people with geological expertise attending the workshop, geothermal energy was also covered.

There were 26 attendees at the workshop (excluding the Fellowship and facilitation team), most of whom were academics and researchers falling within the communities supported by the Natural Environment Research Council (NERC) and the Engineering and Physical Sciences Research Council (EPSRC). In addition, a number of attendees were from private sector and government organisations.

The meeting was professionally facilitated by the Centre for Facilitation Services Ltd in association with the RCUK Energy Strategy Fellowship team. This record of the meeting is a working document, intended to capture the outcomes of the workshop. It represents an intermediate step in the production of full Energy Strategy Fellowship report, which will set out the prospectus for energy research and training in the fossil fuels and CCS areas. It has two purposes; a) to provide a resource which can be "mined" in order to produce the prospectus document; and b) to provide an account of the workshop for comment by the attendees and for archival purposes.

2 Introductory Workshop Session

Jim Skea presented a brief overview of the Fellowship team's progress towards the Energy Research and Training Prospectus, including a digest of outputs from the first two strategy workshops on energy strategies and research needs and the role of the social and environmental sciences[1]. Jim also presented a 'thought diagram' showing the relationship and overlap between the fossil fuel and CCS skillsets (Figure 1).

[1] The Fellowship team held two one-day workshops in 2012 looking at broad UK energy research strategies; '*Energy Strategies and Energy Research Needs*' and '*The Role of the Social and Environmental Sciences and Economics*'. Detailed reports from these workshops, as well as further information on the prospectus-writing process, can be downloaded from the Fellowship's website at http://www3.imperial.ac.uk/icept/ourresearchactivities/rcukenergyprogramme

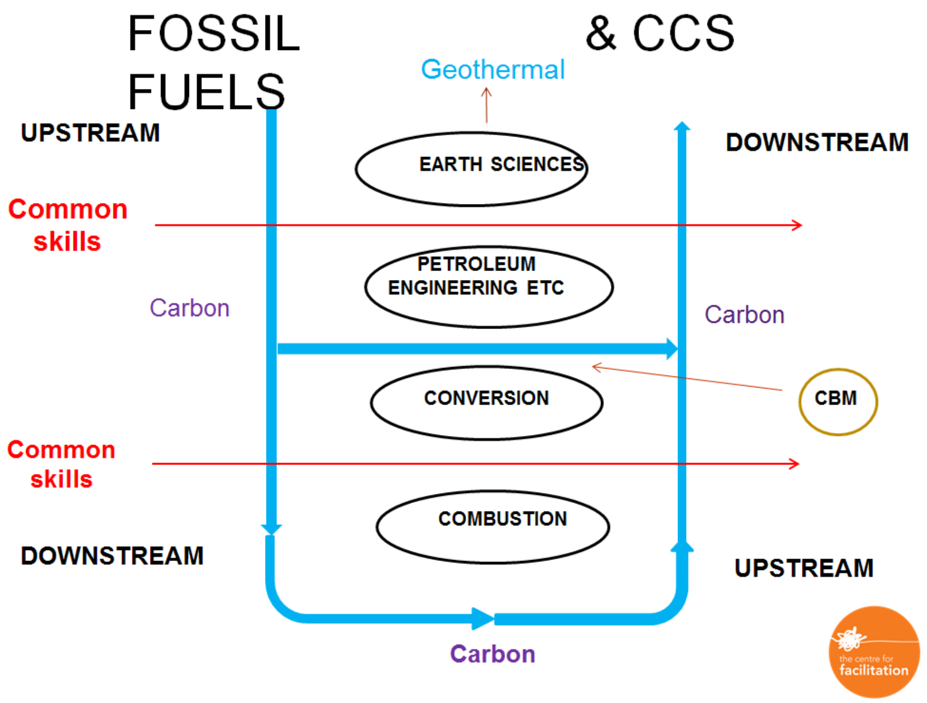

Figure 1 Conceptual diagram to illustrate the relationship and overlap between the fossil fuel and CCS skillsets

Following this presentation, participants were invited to individually record their initial reactions to the strategy workshops outputs, separated into three broad sections, *Delighted, Surprised and Disappointed*. These were written onto sticky notes and placed into three columns (Table 1 Attendees' responses to previous two RCUK ESF Strategic Workshops

).

Surprised	**Delighted**	**Disappointed**
People seemed to 'expect' a greater proportion of CCS energy than 'prefer'.	That CCS and oil and gas have the largest circles in the diagram from the first strategic workshop.	Public communication and perception is not supported as a key topic.
Surprised that geothermal in considered low relevance to the UK.	That expectations on CCS are in line with its predicted contribution to the energy mix.	The interaction of biomass and fossil fuels isn't obviously addressed.
Surprised at strong nuclear and CCS showing.	That there is felt to be no international lead on CCS.	Total energy needs to be considered – not just electricity.
Surprised on the focus on traditional generation systems.	That affordability is getting some attention.	At the lack of separation between electricity generation and fuel use.
Surprised that the social science workshop was difficult to summarise.	At the recognition that the Research Councils don't really encourage interdisciplinary research.	View of CCS not real – everyone talking about it, but no action at scale.
Surprised that the UK doesn't consider itself an international leader in CCS.	At seeing some data on comparative industrial and scientific strengths.	No indication of science + technology 'people' in years to come – succession plan.
Lack of looking at storage and climate engineering.	At looking at both national/international and	Summary didn't recognise growing use of coal + the role

	public/private.	of shale in decarbonising the US.

Table 1 Attendees' responses to previous two RCUK ESF Strategic Workshops

Following the individual reactions, the participants were divided into groups for a few minutes in order to discuss their thoughts, before choosing a point per group to raise in plenary session.

- There was disappointment about the mismatch between what people agree needs to be done and the means and speed that things actually roll-out. People need to be more realistic about the lack of interface between aspirations and delivery.
- One group was delighted to see general agreement and convergence between what technology people expect to see and how this compares with major scenarios and policy aspirations – but there are also some important discrepancies, for example in the unabated gas and renewables sectors.
- There was delight to see focus on applications, but surprise to see not as much focus in what areas to look at in particular workshops. There was disappointment not to see more contributions and scenarios from companies, given that they have to provide a lot of the funding.
- There was concern about fragmentation in thinking, as energy research tends to form 'silos' around different sectors of energy and different disciplines. For example, there are issues in technology areas such as CCS and shale gas bringing up problems with public acceptance, which need to be considered by social scientists.
- Some were surprised that the scenarios reviewed were conservative and seem to be quite strongly based on Business As Usual centralised supply models. Is there a lack of faith in technology development?

Jim Skea then briefly responded to these points. He pointed out that the primary audience is the Research Councils, so although industry input was essential, publically funded research efforts were the priority for the prospectus. The expert workshops have been designed deliberately to avoid the problem of fragmented thinking and silos by aggregating similar disciplines and skillsets together. For example, this workshop contains geothermal energy as a subject, as the skillsets are very close to fossil fuels and CCS. Finally, he mentioned that the workshop reports are records of the discussions that took place, and don't represent the Fellowship team's final view on particular subjects or sectors.

3 Scoping the Research and Training Landscape

The meeting divided into four randomly assigned groups. People made notes individually of the big questions they were dealing with and subsequently presented them to colleagues round the table. The groups collectively developed "mind maps" on flip charts on the tables. The groups then discussed and distilled the key themes, transposing important themes to post-it ovals. Finally each of the groups presented their conclusions back to plenary.

The groups' conclusions fell into three broad areas: policy and the wider context; key research questions; and skills/training needs. The group discussions covered a range of technologies including CCS, geothermal, underground coal gasification (UCG), fossil fuel use and unconventional gas as well as many cross-cutting issues. The outputs are captured in the following table (Table 2). However, it is worthwhile noting some strong emerging themes:

- The applicability of science and engineering skills across a range of technologies implying a need for transferable skills;
- Synergies between technologies, e.g. CCS and UCG;
- A need for better links between sub-surface science and engineering; and

- The importance of public engagement and understanding of public perceptions of sub-surface activity.

Application	Policy and wider context	Research questions	Skills/training
CCS	• Lack of momentum for CCS due to financial climate and low priority of climate change policy • Development needs to be compared to development of N Sea oil; major national commitment • Treat CCS like renewables	*Capture* • Gas separation • Process scale-up • Materials development • New CCS technologies • HCV gas • Pre-combustion gasification – catalyst/absorbent interaction *Transport and storage* • Work on public acceptance • Whole systems perspective on issues such as CO2 purity across transport/storage/ EOR • Phase behaviour of CO2 in transport	• Level of need for capacity building given long deployment timescales? • Conversely, lack of skills is impeding CCS deployment? • Transfer of subsurface skills
Geothermal	• Lack of incentives	• Capacity assessment • Environmental impacts • Synergies with CCS	• Need transfer of skills/ technology from oil and gas
UCG	• Commercial scale needed to advance understanding	• Environmental impacts of UCG • Interaction between UCG and CCS – UCG creates potential CO2 storage capacity	
Unconventional gas		• Return of additives to the surface	• Need trained people for operations as well as research
Fossil fuel		• Links with biomass • Control systems and flexibility • Fuel flexibility • Enhancing efficiency through higher operating temperatures	
X-cutting	• Deep saline aquifers available but not close to demand • Financial barriers for real projects • Low levels of quickly usable coal reserves and gas storage • Public engagement in relation to sub-surface activities • Financial barriers for real projects	• Techniques similar to fracking needed for saline aquifers • Understand interface between what is engineered and what happens naturally at the sub-surface • Integrating geochemistry science with reservoir engineering • Water/chemical interactions in reservoirs/impact on prosody and permeability • Availability/capacity of subsurface resources • Minimisation of surface disruption • Public perceptions of sub-surface activities Bringing together sub-surface	• Developing flexible skills among students/researchers • Develop people conversant with multiple disciplines, including social sciences • Technologies use same basic science – enhance transferability of skills

		science and engineering	

Table 2 Key research challenges across these dimensions of the fossil fuels and CCS research area

A number of other broader issues were also raised in plenary discussion:

- The RCUK role in fossil fuel research and geothermal needs clarified
- What is the role of RCUK vis-a-vis other bodies in relation to technology promotion?
- Research planning must be robust against uncertainty
- Recognise global nature of research. UK research has influence internationally, but we need to take account of developments overseas.
- Encourage people with the right skills to enter the energy field given uncertainties.
- There is a lack of skills in the workforce. European countries are recruiting in the US
- How can CCS RD&D be financed?
- Make the best use of existing wires and pipes infrastructure.
- Many believe that the UK should increase indigenous fuel production

4 The Research Context: Café Dialogue Session

This session allowed workshop participants to flexibly discuss issues surrounding the current and future development of research in an informal setting. The exercise began with the four table hosts introducing themselves and their questions for discussion. Following this, participants moved to the table which most interested them to discuss the questions further. Participants were encouraged to actively contribute to the discussion, ensuring that their perspectives and experiences were added to the dialogue. People were encouraged to switch between tables regularly, ensuring that they contributed to several of the discussions on offer.

The four discussion areas were:

- Carbon capture from air
- The interplay between shale gas and coal prices
- Is CCS only a temporary fix?
- Uncertainties surrounding energy scenarios

4.1 Carbon capture from air

This table looked at the feasibility of capturing CO_2 directly from the air, instead of from the burning of fossil fuels. They began with defining air capture – what technologies are included? The concept of burning biomass and capturing the emitted CO_2, known as Biomass with CCS (BECCS) was considered to fall under this definition. Direct Air Capture (DAC) where CO2 is removed by scrubbing from atmospheric air was the other major technology defined to be relevant.

There was a general consensus that direct air capture should only be implemented after other easier abatement options are implemented, but evaluating the costs of direct air capture is still important, as it effectively puts a maximum price on carbon. There was considerable discussion over the economics of direct air capture, and under what conditions it would be cost-effective. Direct air capture may need to be distributed and small-scale, which raises infrastructure issues. There was one comment on the fact that the realm of the cost of direct air capture is in the realm of what people currently pay for abatement from renewable energy sources. Direct Air Capture may be more effective in colder areas of the planet, as the process is more thermodynamically favourable. Several commented that the problem is fundamentally with CO_2 emissions, and not a lack of fossil fuels. If a global agreement constrains carbon emissions, the price of fossil fuels may fall to their marginal cost of production, due to oversupply.

Public perception of air capture is mixed. Direct air capture is disliked by some because it could be a ‘get out of jail’ card to allow people to continue using unabated fossil fuels. It could be considered to be analogous with geo-engineering. However, geo-engineering is well-received by the public, perhaps because it uses ‘natural’ methods. How do the benefits and costs of direct air capture compare to deforestation management?

4.2 Shale Gas

The US is starting to use less coal in the face of their growing reliance on shale gas. It was explained by the host that shale gas was attractive to the US due to its low prices as well as gas plants being able to be built relatively quickly. Much of the coal no longer being used by the US is being transported to the EU due to depressed prices caused by this US coal oversupply. The EU is therefore beginning to use much more coal despite their regulatory stance, which is broadly supportive of low-carbon generation.

The discussion started with the key question being raised that this kind of unpredictable event (the increase in coal consumption due to the development of the US shale gas industry) could happen again sometime soon. Should we be stepping up efforts to research these areas of uncertainty? Another uncertain area that was raised is whether we have sufficient knowledge of the potential threats of shale gas extraction to be able to regulate it effectively. The UK is known to have strong capabilities around offshore extraction, but does not possess as much knowledge and experience in onshore extraction.

The US has had very significant growth in shale gas extraction in the last few years. People thought that there were several differences between the US and UK markets, including land ownership – in the US, if someone owns land they also own the mineral rights. In the UK this is not the case, as the Crown owns rights to minerals below the surface. This means that it will be harder in the UK to win public support and engagement for shale gas projects. The UK is also far more densely populated than the US and will have fewer resources overall. There was also a point raised about risk – the US is seen as less risk-adverse than the UK, meaning their industry would not face as lengthy or rigorous regulatory processes, and less public opposition on risk and environmental grounds. The US also proceeded with shale gas with a much lower research base than would be expected in the UK. Shale gas in the US was seen from the outset as something inherently profitable – this led to a large quantity of research being funded from the outset by private industry.

It was thought by the group that the hurdles surrounding shale gas extraction in the UK fell into three main groups:

- Exploration/appraisal - issues with opposition
- Pilot programmes
- Commercial Production

It was said that there is a long gestation period for a shale gas industry to mature. Industry needs to know where commercial quantities of gas are, obtain licences and allay public fears. R&D efforts need to be undertaken also to determine the best methods and technologies to use in UK shale gas extraction. In the US, some members of the group felt that there had been issues in terms of not drilling deeply enough and drilling too near to aquifers. Issues around these have not necessarily been proven. There are opportunities for further research in the UK on these areas.

The question was raised: 'What is the RCUK's role in terms of shale gas research?' One response was a better characterisation of UK shales. Also, research into how industry might allay the public's fears about shale gas extraction.

4.3 Is CCS only a temporary fix?

This table asked the questions: Is carbon capture and storage only a temporary solution to climate change? Is it a technology which is designed simply to reduce carbon emissions from fossil fuels, and not a long-term solution to the climate problem? If so, is it worth the financial investments and time required to turn it into a functional commercial technology?

The discussion started with the statement that it is important to be realistic that decarbonising will cost money. There is a lot of inertia in the system and if we're serious about decarbonising we need to be serious about paying for it. One historical implication for the UK is that we have a centralised system built on fossil fuel input. There is a lot of inertia in the system.

Is it really possible for the UK to 'go it alone' and take the lead on developing CCS technology? The UK seems to have significant renewable resources, particularly in Scotland, and perhaps a new-build programme of nuclear in the future. It seems clear that the state will have to intervene to make CCS viable in the UK. For CCS, the proposals are for a small number of large projects. These are risky for funders. This could be seen as a failure of market economics, since projects with high downside risk and only moderate potential upside return cannot make progress easily, especially as CCS projects are competing against potentially much more significant revenues from big oil projects. Should the UK be considering smaller CCS trials, on the order of a few hundred MW, rather than the large 800MW-1GW trials currently planned? This could make the risk profile more acceptable, as well as providing a greater variety of trials.

CCS and other energy technologies can be seen as 'local' solutions to the 'global' problem of climate change. CCS may well be suitable for Europe, with a centralised generation system and often accessible storage, but can the technologies be deployed at scale globally, with many other countries having more distributed systems of generation and possible storage sites. It was suggested that we should be looking more seriously at two-way technology and knowledge sharing between developed and developing countries. The UK is the only country currently developing a mechanism, contracts for difference within the Electricity Market Reform proposals that can address the need to cover operating costs as well as upfront capital expenditure. This could help deployment of CCS in the UK, but will not help break down every barrier. It was the view of several of the group that CCS will need to be deployed soon – otherwise it may be a better plan to progress geo-engineering and gen IV nuclear technologies to address carbon emissions.

4.4 Uncertainties surrounding energy scenarios

Currently, there are several major scenarios and models suggesting how the UK energy system may develop to 2050 published by the UK government (DECC), advisors, academics and industry. The Fellowship team attempted a meta-analysis of these scenarios in order to elicit both commonalities and differences[2]. This analysis showed considerable uncertainty between scenarios, both in the pathways to meeting our carbon emission goals as well as the makeup and mix of energy supply technologies and fuels. This table was given the task to explore these uncertainties as they pertained to the fossil fuel and CCS sector.

[2] The preliminary findings from the scenario meta-analysis can be downloaded from the Fellowship's website at http://www3.imperial.ac.uk/icept/ourresearchactivities/rcukenergyprogramme

A common viewpoint was that the UK comes up with a lot of ideas to arrive to a low-carbon future, but has difficulty in implementing the ambitious programmes of work that are required. A 'quick-and-dirty' solution presented was simply for the country to choose its 'top-3' technologies and put the vast majority of research and deployment resources into those. A more detailed solution could take the form of a forecasting roadmap which detailed the steps in research, demonstration and deployment of technologies required to reach a scenario outcome. This could however be difficult practically – a prescriptive roadmap would be difficult to implement over a timespan of decades.

The overall view of the table is that new gas generation is probable in the UK, and that shale gas will be developed, though the extent of this was disputed. It is possible that UK research on shale gas will be exportable worldwide, as the problems we may encounter will be different to the US experience. It was proposed that US shale gas prices are too cheap currently due to oversupply – with time the prices will increase, perhaps dramatically. In addition, US prices are no guide for the price of gas in the UK – gas prices are determined on a per-territory basis and the US has little significant gas-exporting capability. The UK has very few policies currently on fossil fuels – most of the policy effort has gone into supporting renewables and other low-carbon technologies. This could account for unabated gas's relative unimportance in most future scenarios – these scenarios are designed to reach a carbon emissions target, not necessarily focusing on price or energy security.

In the case of CCS, many scenarios forecast a relatively high proportion of coal CCS in the future energy mix. It was stated that these scenarios do not fully represent current thinking, and that gas CCS and bioenergy CCS have become much more relevant with the rising importance of shale gas. Research in storage methods does not vary much with the input fuel – however capture methods differ substantially, and more research on gas CCS especially would be needed. However, storage currently poses the greatest research challenges, and the general view of the table was that successful large-scale CO_2 storage is still a way off. The basic skill sets of geo-mechanics and geo-chemistry are transferable between these disciplines, and there will be a strong demand for people trained in these skills regardless if CCS becomes a major UK player.

5 Research Capabilities: Where Are We Now?

Working individually, people were asked to identify where they thought we are now in terms of research capabilities for tackling future energy challenges. They were invited to score these on a scale of 0-10 (0 = no chance, 10 = well setup) and explain their score on a post-it note. The following graph shows the distribution of the 32 post-its. The average score was 4.9 +/- 2.5. The following three tables, dividing the results into three classes: low capability (0-3); medium capability (4-6); and high capability (7-10), set out the detailed results. A strong theme running through the post-its is a request for more action from government and industry to exploit research capabilities. Will non-researchers see it this way? The results are set out in below (Figure 2 & Table 3)

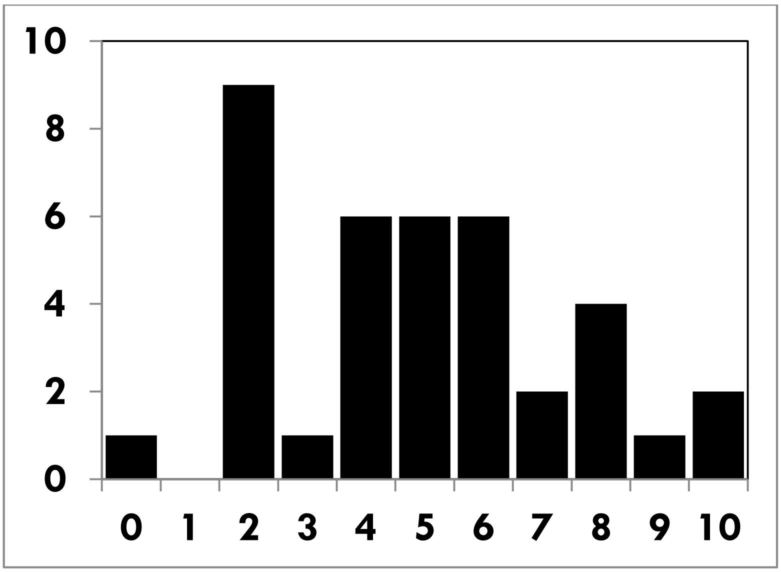

Figure 2 Distribution of perceived UK capability levels

High capability levels			
7	**8**	**9**	**10**
Tools and expertise to do good research on CO_2 storage, but lack industrial engagement and field experiments	Fundamental scientific and engineering understanding for CCS/oil and gas	CCS capture technology	Best in world at promises for CCS but much of it is political hot air!
System simulation of CCS	Research capability high but poorly linked to industry/government		Enhanced oil recovery. We have the tools and expertise but needs to be seen as a natural resource to maximise opportunity
	UK reputation		
	CCS		

Medium capability levels		
4	**5**	**6**
CCS storage: enough to start not enough for big investors	Good research for enabling CCS, but "valley of death" problem and policy slow	Interface between science, engineering, law and economics to develop CCS framework
Engineering impacts on subsurface; know the basics but need further development interacting with field projects	CCS/enhanced oil recovery: lots of potential and knowledge but no application	Efforts dissipated because we hedge our bets against uncertainty and lack technical leadership
Monitoring and verification of stored CO_2	Bright intelligent people to deliver the research challenge, they need support to deliver impact	CCS well-placed after a late start. Need industry action
Role of industrial research not identified, especially for non-conventional hydrocarbons	We have technical ability of CO_2 storage but no clear expectations of where we are headed	Building blocks are in place to meet CCS technical challenges. Funding and policy will drive uptake
Lack of facilities for large-scale CCS research	Deep specialist expertise available but lack technical leadership and system integration	Improve engagement with social science
Fundamental understanding OK but application poor	Lack of demonstration for some technologies	Well set up but lack political will/social urgency

Low capability levels			
0	**1**	**2**	**3**
Hydraulic fracturing		Loss of UK industry leaves hole in capacity	Lack of people with skills and experience across the fossil fuel/CCS domain

		Tiny pockets of sub-critical expertise and funding	
		Geothermal	
		Lack of joined up thinking on energy security	
		Knowledge and techniques relating to deep geology onshore	
		MSc/PhD funding for subsurface training	
		CO2 storage	
		Fragmented Research Council activity	

Table 3 UK's current levels of research capabilities across the energy sector

6 The Backcloth to 2020-2050: the PESTEL framework

The meeting broke into four groups that explored wider trends that could form the backcloth to developments in the period 2020-2050. The PESTEL (Political, Economic, Social, Technological, Environmental, Legal) framework was used as a guide. The groups recorded their thoughts on mind-map flipcharts. The following constitutes the key outputs from the four groups according to the PESTEL framework.

6.1 Political

General

- Political trends are uncertain, as are trends in fossil fuel use, although growing consumption in developing countries is likely.
- Rapid build-up of new gas seems likely
- Catastrophic climate events?

Geopolitical

- Diminishing influence of Middle East as gas and (dirty) coal overtakes oil as primary energy source. Shift in global balance of power.
- Arab Spring/political instability
- Loss of US interest in Middle East as a consequence of self-sufficiency - political instability in our major oil supply.
- Coal supply is politically safe
- Qatar rather than Saudi Arabia is a major player in gas supply

New sources of supply

- Impacts of shale gas unclear.
- Opening up the Arctic
- Tar sands

UK Issues

- Consistency in policy/long-term planning
- Potential impact of Electricity Market Reform.
- Security of supply (e.g. imports from Russia, dependence on high capacity pipeline from Norway)
- Concern about climate and prices likely to diminish if the lights go out.
- Contractual security and affordability
- Affordability, fuel poverty continue to be important

6.2 Economic

Economic background

- What does the UK need to do to continue be a major economy in the 2020s?
- A big rush from the pound caused by the euro recovery?
- Post-austerity by 2020? Rebound in electricity demand, less risk-aversion in the private sector, less constrained public sector budgets

Energy markets

- Increasing rates and quantities of fossil fuels, with China, India and US consuming 75% of coal.
- Domestic UK energy supplies over different timescales?
- Imminent power plants closures, what will replace them
- Volatility of fuel prices

Markets and investment

- Market/investor confidence
- Subsidies - who pays for investment?
- Competitiveness of energy-intensive industry

6.3 Social

General

- Decreased environmental concerns amongst a fraction of the public; lack of awareness of climate change plus climate scepticism
- Lack of awareness of where electricity comes from
- Democratisation of information but "dumbing down" and loss of trust in science and engineering

Technology acceptance

- Public perception/acceptability of new technologies (shale/geothermal) and greenfield power plants
- Onshore unconventional fuel extraction: perceptions of earthquakes, leakage, contamination
- Land use pressure
- Influence of vocal minorities
- Management of expectations/public dialogue
- Community energy schemes could offset nimbysm
- Stakeholder acceptability of research/pilot projects

Affordability

- Energy poverty/energy access
- New technologies add to cost with implications for energy poverty.
- Redefinition of fuel poverty?

6.4 Technological

General

- More electricity in future scenarios
- Disruptive technologies
- Insufficient broadband?

Technology management

- Risk-aversion of policymakers/industry to new technology
- 3D subsurface planning

- Increasing complexity of technological systems
- Demonstrators of integrated systems/new technologies
- Step change technology needs large capital investment
- Scalability

Specific technologies

- Grid scale storage
- Design and develop 'cleverer" systems to maximise thermodynamic efficiency

6.5 Environmental

General

- Availability of natural resources for energy
- Scarce materials for specific technologies
- Risk mitigation/contingency

Climate change

- Impact of climate change globally and locally
- Is cost of climate change adaptation relevant in the 2020-2050 timescale?
- If we are rich enough could we choose to adapt, or spend money now on mitigation? How will this play out in different parts of the world?

6.6 Legal

General

- Legal risks for individual scientists (e.g. Italian earthquakes) could constrain dialogue around risk
- Planning and permitting
- Mitigating risk and enforcing best practice
- EU2020 targets

CCS

- Regulation onshore/offshore
- A legal maze onshore: no co-ordinated framework in place.
- Possible legal barriers to international transport of CO_2
- Unintended consequences: OSPAR and London Conventions had unexpected consequences in terms of offshore waste disposal
- Legal element needed for research.

Climate Change

- No comprehensive international legal framework for climate change
- Legally binding climate targets: will they be complied with?

6.7 Cross-cutting and other issues

- Need to take an international view, not just the UK perspective

- Environment, energy security and cost are constantly pushing/pulling in different situations. Each has dominated the agenda in the last 20 to 30 years.
- Availability of expertise

7 "Hotspots" for Future Research

This exercise asked participants to imagine what the potential 'hotspots' were for research for the years 2020-2050. Attendees were individually asked to note some ideas on hotspots, before moving into pairs to discuss and clarify their thoughts. These pairs then moved into self-selected groups, who formed 'clustered' the hotspots around common themes, skillsets and uses. The groups than nominated a spokesperson to report back the ideas in plenary.

The hotspot data is recorded in the below tables, with the left-hand side columns being the clusters, and the right-hand side being the ideas 'below' the clusters, i.e. the 'hotspots'. Notes from the plenary reporting are also enclosed.

7.1 Group 1

- Synergy between different groups, but CO2 capture from air out on its own
- Clusters – linked by integrated systems, conventional technologies/business should be connected with new/emerging ones (CCS and EOR, CCS and biofuels, UCG with geothermal)
- Want to look for integrated systems to improve fuel efficiency – also large storage projects and control of systems/materials for more efficient and better utilisation of energy source
- Coherent long term training plan needed
- Materials/sensors etc as underpinning activities
- Not just enough to think about doing CCS and monitoring what is happening, but want to be able to control what is happening in the subsurface (manage it and make things happen)
- Deep subsurface is out of equilibrium with the surface, so deep subsurface pulls it all together
- Quite a few pilots up here – not just testing stuff in the lab, but need to be doing stuff at medium scale in the field (data for calibration etc)

Super Cluster	Clusters	Hot Spots
Integration – Heat/Kinetics -> Utilisation		
	Large Scale Storage	
	Life Cycle Assessment – optimised by smart materials + structures + intelligent control.	
	Geochemistry	Comprehensive programme on multiplex + reactive fluid flow
		Reservoir Geochemistry
	Geothermal + CCS + UCG + CBM + Shale Gas	

		Demonstration of large scale integration of related systems
		Linkages between conventional + new technologies and businesses
		Geothermal electricity interconnector from Iceland
	2020 – subsurface CCS pilot with monitoring and control.	
	2020 – enhanced geothermal pilot (water added at depth).	
	2020 – efficient energy storage pilot.	
	2030 – Follow-up to full-scale pilots.	

Table 4 Energy research clusters and hotspots: Group 1

7.2 Group 2

- New technologies – industrial capture, air capture, biomimetics (quite broad scope of things covered within this)
- Improvements in what we think we can do (e.g. improved capture technologies)
- De-risking and removing barriers for all technology areas covered here (similar skills needed)
- Technical geochemical stuff (fluid interaction in all cases)
- System interaction in all cases (e.g. pipeline examples)
- Economics – how can we get round it and make it work for us?

Clusters	Hot Spots
New Technology	
	Industrial CO2 capture and transport clusters
	Carbon capture from air + deployment in the UK. Regulation, environmental impacts, effectiveness.
	De-risking of CCS storage
	Developing coal-based CCS to be cheaper than natural gas.
	Biomimetic CO2 transport/capture/storage processes.
CO2 Capture	
	Capture from gas
	Gas CCS retrofit for UK conditions

Economics	
	Financing CCS through better usage of subsurface
	Government role in leading and nudging
	Changing portfolio management – more low carbon products
Systems + Transport	
	Low-cost CO2 corrosion inhibitors for water etc. with carbon steel
	Integration along CCS chain –impurities and rates.
	LNG-Shipping-CO2 co-location.

Table 5 Energy research clusters and hotspots: Group 2

7.3 Group 3

- Their ideas fell along a timeline, so sorted it that way
- Shorter term (2020s deployment) – CCS cropped up a lot, optimising current generation of technologies. Getting costs down etc and making best use of existing resources. Still stuff missing for these close to commercial technologies.
- Next generation for 2030s deployment then follows (e.g. membranes, CCS on gas, adsorbents, calcium looping etc). Also get beyond sequestrating CO2 – but actually use carbon directly (take the logic of biochar, but going beyond that) and additional link to CO2 utilisation for fuels and chemicals.
- Then also have 2030+ future gen technologies category, so totally new types of capture (e.g. anti-sublimation materials, metal organic framework (MOF) liquids, decarbonising at source so that carbon never gets to the surface – downhole chemistry)
- Also need to think about common approach to risk mitigation
- Links to 2030+ ideas with things that are a bit off-topic for this workshop include negative emissions (combinations of nuclear and fossil), new energy carriers and distributed generation, small scale capture, community buy-in (reward for taking risks), electrification of cities and perhaps linked energy storage.

Super Clusters	**Clusters**	**Hot Spots**
Short-Term		
		Joint dev of fossil fuels and biomass needed – the two are not independent.
		Maximise existing resources – natural or built.
		Look at how to reduce major costs
		Novel structural materials for power plants, capture units, pipelines etc

		Need to focus on cross-disciplinary integration.
		Investigate market reform
		Legal and regulatory issues
Mid-Term		
		CO_2 capture and utilisation for fuels & chemicals
		Next gen CO_2 capture (mid 2020s) membranes/gas CCS/adsorbents/carb. looping
Longer-Term		
	'Community' concepts	
		Encourage community buy-in – with risk comes shared reward
		Small-scale generation and carbon capture at domestic levels
		Common approach to risk mitigation underground.
	Demand side drive (2030+)	
		'Fossil+CCS' in green-city context
		Ensure scaleability of technology to match end-user needs.
		New energy carriers (H2/batteries) topped up by fossil, renewables, domestic generation.
	Technology merging (long-term, 2030+)	
		CO2 negative technology integration – renewable energy and nukes with fossil (way China is thinking)
		Is future use in shared, centralised or local, domestic technologies?

Table 6 Energy research clusters and hotspots: Group 3

7.4 Group 4

- Step-change research (e.g. CCS examples) – potential to make big difference such as air capture, recognising that coal is going to be around for a while (comparative with gas)
- Cross-learning – monitoring and related public perception of all technologies, geochemistry (CCS, fluid flows and links to other industries – metals for renewables come together in ores with fluid flow in the subsurface dictating where resources are found)
- Compressed air storage, other flows underground and heat storage underground (e.g. with fracking?). Geothermal electricity as an outlier (interconnector to Iceland – what impact?, would this knock-out certain things in the UK mix, moving on to super-grids more generally perhaps also solar from Sahara?)
- Bioenergy and CCS not covered much here, but also potentially important. Perhaps to be followed up in broader picture of best use of biomass in the biomass workshop?

Clusters	Hot Spots
Cross-learning	
	Research to allay public fears about CO2 storage.
	Use of social media to improve public acceptability.
	CCS in isolated areas – affordable pipelines and low risk to people.
Coherent long-term training	
	Subsurface training for UK needs MScs and PhDs.
	CCS Skills in subsurface, Geoscience and Geoengineering. Premium PhD payments? Selective immigration of talent.
	Skills training needs to take account of age, gender etc.
	Underpinning science to maximise efficiency, minimise cost, make better use of resources.
Geochemistry and sub-surface	
	Fluid-rock interaction
	Heat- Fracking research. Cross sector – can geothermal learn from oil/gas?
International research	
	International impact of US research – team work required.
	International research collaborations – to take the best from around the world and build on it. UK tech. doesn't need to be deployed in the UK.
	Can't ignore the USA and China, who will drive the fossil fuel world.
Capture and transport	

	Small-scale CCS plants for agile power generation. Needs a different technology base.
	Flow characterisation at large spatial and temporal scales.
	Health implications of capture chemicals and transport.

Table 7 Energy research clusters and hotspots: Group 4

8 Have We Missed Anything?

As part of this activity the delegates worked individually, selecting random images to act as a prompt to generate any thoughts/questions in relation to the hot spots or help to identify new hot spots. They were asked to record these ideas on post-it notes. They were then asked to work as pairs in order to share their insights with their partner and identify any important emerging themes to add to the hot spots.

The nature of this activity means that the specific outputs were not captured but were passed on to the subsequent session on *emerging research challenges*.

9 Emerging Research Challenges

9.1 Methodology

For this exercise, participants were asked to record their thoughts on the emerging research challenges for the fossil fuel and CCS sector, and their reflections on these challenges. They were then asked to pass their pads to a colleague so that they could record their thoughts and observations. Groups were then asked to discuss their comments with the group before passing their records to the facilitation team for safekeeping.

9.2 Subsurface Challenges

The subsurface is clearly a major research arena for the future, both in extraction and disposal/storage. It was felt that a more unified approach, with public engagement an essential part of the process, is required to address/identify subsurface challenges. The key themes that emerged relating to this subject included:

- The need to understand how the deep subsurface will be affected by engineered activity – critical to the reception of many energy technologies. Key points where the impact of particular behaviour could be game-changing.
- More complex characterisation and use of the subsurface system. This includes the reactive and flow properties of the subsurface as CO_2, brine and hydrocarbons flow during both production and storage. There is a need for an interdisciplinary programme between NERC and EPSRC.
- The subsurface is heterogeneous, so sometimes generic research contributes little at the specific project level. Need to move to more pilots/demonstrations.
- The need to learn more about management of the subsurface including pressure management, space, efficiency, safety, security, heat. How is it done and who does it?
- Do we understand the political vectors and social acceptance factors for shale gas adequately?
- There's a challenge of ensuring that research on 'unconventional energy' (gas hydrates and UCG, not just shale gas) take a 'whole systems' approach.

9.3 CCS

Storage and utilisation of CO_2 came up repeatedly in this section and in the research clusters. Interestingly, storage and subsurface challenges seem to be the largest emerging research clusters. The key themes that emerged relating to this subject included:

- What are the fundamental implementation differences between CCS and other low-carbon technologies? How can we bridge the difference?
- CCS needs research efforts moving towards demonstration and deployment – high-risk, high-reward, patentable, licensable technology. Is a major injection of public sector finance needed, and can CCS ever provide a good return?
- Large-scale energy storage to couple to large-scale CCS technologies?
- Are synergies between the electricity and chemical industries being missed e.g CO2 as a chemical feedstock, syngas for electricity and chemical production, shared infrastructure?
- CO2 captured could be used for EOR or as a geothermal fluid.
- Integration of biomass in CCS – research challenges surrounding this, including balancing of masses at large scale. Leads to negative emissions.
- There is a desperate need for learning by doing currently in the CCS community – need to understand more fully the economics and regulation around CCS.
- Research on CCS should focus on reducing cost and increasing security. The problems currently are economics (investment cost) and regulation.
- Do we need to research novel combustion technologies for fossil fuels? Research needs for 'conventional power' not widely mentioned.
- Long-term research should have the goal of making coal CCS cheaper than unabated gas power plants. Should have a long-term goal of ramping down CCS research and ramping up pilot and deployment schemes.
- Research should move towards getting CO_2 to be considered a valuable commodity.

9.4 General/nonspecific

Training a new generation of researchers and engineers in the fossil fuel/CCS world was a point brought up by many attendees. A multidisciplinary, basic-skills training programme was the favourite, giving graduates and post-graduates the ability to move between different disciplines in this sector. The key themes that emerged relating to this subject included:

- Time cost of climate change to highlight incentives vs cost of doing nothing. More practicality, climate change means we need work quicker, as long deployment lead-times are needed.
- Could we do decarbonisation 'down the hole'? UCG -> Syngas (CO_2 + H_2) -> H_2 only coming out the surface? The difficult bit would be reingesting the CO_2. Could extract high-grade heat only.
- Capacities and skills – not enough younger people being trained. Need to cope with uncertainty as well as external influences on the UK.
- One attendee wrote that they believed that the challenge for the future is not research, but implementation of existing technologies of scale.
- Geothermal technologies need clear UK-focused research and technology development.
- How do publically-funded research and industry work together? Shared results from industry can be of great help to researchers.
- Multidisciplinary research needs to be implemented, not simply aspired to! Systems and structures should be set up by the research councils.

10 Research and Training Needs: A Deep-dive in Communities of Interest

Participants self-selected to form five groups based round "communities of interest". The five groups were:

- Group S: Sub-surface
- Group E: Engineering and systems
- Group I: Impacts
- Group T: Training
- Group X: Technology development and users

The groups were then invited to explore seven questions relating to future research and training needs in the Fossil Fuels & CCS area:

1. What are the most important fossil fuel/CCS applications for your community?
2. What are the key research questions?
3. What capabilities / capacities do we need in place for the UK to address these applications?
4. What challenges will we face?
5. Where are the shortfalls?
6. What might / should we do to make ourselves 'match-fit'
7. PhD training? Research Infrastructure / underlying facilities? Funding philosophy?

10.1 Community S: Sub-surface

What are the most important fossil fuel/CCS applications for your community?

Premises:

- Important to separate resource issues from safety issues; Research Council resources should be for the public good – do not duplicate private sector funding

Specific issues:

- The UK is resource rich and there is a need to capitalise on that strategically
- Making the transfer from physical resources to economic reserves. Subsurface science interacts with engineering
- What is the impact for the UK economy?
- There are obvious linkages between oil and gas, underground coal gasification, CCS and geothermal
- How much storage space is available for heat, disposal and re-use?
- How much unconventional gas is there? The public good (Research Council role) is furthered by determining the resource which would allow oil and gas companies to exploit shale gas, coal bed methane and underground coal gasification
- How much remaining conventional oil and gas is there? How much coal? How much heat?
- Then discussion moved on the "flow stream" to go from resources to reserves
- Security and safety issues include leakage of methane and CO_2

What are the key research questions?

- Reactive fluid flow
- Imaging and remote sensing
- Modelling, all scales from fundamental physics at the micro-scale to macro-scale
- "Knowledge based dynamic management"

What capabilities / capacities do we need in place for the UK to address these applications?

- Need people!
- Need large-scale pilots. They require time and to be supported by long-term funding, just by the nature of geological processes.
- Cross-learning between conventional and unconventional oil and gas, coal, CCS, geothermal
- Baseline data and geological surveys
- We don't have the capacity in the UK
- Need engineers to talk to geologists, and vice versa
- Important to work across Research Councils, improve linkages

What challenges will we face? Where are the shortfalls?

- We need more UK ambition – is the UK frightened to be first mover? The likely outcome is "too little too late"

What might / should we do to make ourselves 'match-fit'?

PhD training? Research Infrastructure / underlying facilities? Funding philosophy "Just do it" "& learn on the job"

- Petroleum research has been left to industry, rather than national leadership. This is less true of EPSRC and, internationally, the US DOE
- For example, enhanced oil recovery (EOR) with CO_2 EOR in the USA was, for example, kick-started by tax breaks after an initial steering project supported by US DOE
- The group recommends adopting the US DOE Model with its strategic/proactive approach and willingness to take risks with high cost/high value investments. The result is national value, safety/security and leadership

10.2 Community E, Engineering and Systems

This group discussed five application areas (Q1) and explored research questions for each (Q2). It then addressed more briefly questions 3-7 at a generic level. Three other application areas were omitted due to lack of time.

What is the scope of engineering and systems?

Engineering and system is about getting stuff out of the lab into real world application while responding to feedback from 'real' projects. Must take account of:

- legal constraints
- RAMO (reliability, availability, maintainability and operability).
- Economic and social considerations

What are the most important fossil fuel/CCS applications for your community?

- E1 – CO2 transport by all means
- E2 – Power plants and capture (all sources, including air capture)
- E3 – Integrated systems
- E4 – Hydraulic fracturing
- E5 – Energy Storage

What are the key research questions?

E1 – CO2 transport

- Cost reduction for CO2 transport which is currently overdesigned. Options for removing conservative design and operating practices without compromising health and safety.
- Reuse of existing pipelines
- Non-pure CO_2 and linking mixed input streams (different sources, compositions and flow rates)
- Materials and structural integrity to allow thinner and cheaper pipelines
- Damage mitigation, including how cracks become established and grow and the consequences of pipeline fracture

E2 – Power plants and capture (all sources, including air capture)

- Consider power plant and capture as a system
- Capital cost reduction a priority as well as improved efficiency
- Analysis of the potential for direct air capture
- Value engineering, scaling
- Alternative disposal options linked with other uses of the subsurface

E3 – Integrated systems

- Identification of synergies
- Redefining the boundaries of engineering systems to recognise the potential value of key innovations
- Reframing system boundaries to take account of how primary energy transformation is linked to end use
- Incremental developments as well as step changes
- Potential for carbon negative biomass with CCS
- Heat utilisation

E4 – Hydraulic fracturing

- Understanding and modelling of growth of fractures
- Reducing the cost of analysis tools
- Options, such as better sensors, that would reduce the need for drilling
- Assessment methods for well integrity, use of old wells?

E5 – Energy Storage

- Energy storage needs to view as part of a continuum that includes aspects beyond the scope of this workshop
- Energy storage potential within fossil and CCS systems
- Gas storage

What capabilities / capacities do we need in place for the UK to address these applications?

- Industry is struggling to get good people in sufficient volume with the 'right' background. Some multidisciplinary awareness would be useful
- Industry could be helped to identify and access the academic skills base

What challenges will we face? Where are the shortfalls?

- Critical mass is a problem arising from the piecemeal nature of current funding
- More clarity about has the remit to do what. Some academics think they have a role in developing standards but at least some parts of industry disagree

What might / should we do to make ourselves 'match-fit'?

- Identify and provide long-term support centres of excellence that are able to provide technical leadership
- Avoid random competitive calls that lead to a fragmented community
- Make increased use of reviewers with an industry background as opposed to marginally qualified academic peer review 'experts'
- Improved academic understanding of what is transferrable into industry
- Strong monitoring and reporting processes for long-term funding investments
- Innovation in not linear: the TRL (Technology Readiness Level) is not necessarily appropriate for prioritising Research Council funding
- Industry works mainly through incremental improvements and that needs to be reflected in the RC strategy

PhD training? Research Infrastructure / underlying facilities? Funding philosophy?

- Re-assess policy of not including students on EPSRC grant proposals by talking a broader definition of a 'cohort' of students
- Ensure that straight to research PhDs without an additional taught year continue to be available. Students do not always want or need an additional taught year
- If PhD numbers are restricted too much then there will be a problem getting good people out from academe
- The decision to stop funding PhD students on research projects has led to a big gap in the supply of trained people
- Use national research centres to allow targeted development of consortia in key areas
- Appropriate shared facilities are needed
- The current research programme is not very good at delivering integration. Centres achieve integration and are thus important

10.3 Community I: Impacts

General

- We need to have regulations in place to do anything

What are the most important fossil fuel/CCS applications for your community?

- Hydraulic fracturing - not a new technique and not only used for shale gas.
- Underground storage: CO_2, heat, compressed air

- Recovery from underground reservoirs (e.g. enhanced oil recovery)
- Injection (CO2), fluids for hydraulic fracturing
- Underground coal gasification
- Methane hydrates
- Tight gas
- Coal bed methane
- Biomass CCS
- Geothermal (shallow and deep)
- Air capture (CDR = carbon dioxide removal)

What are the key research questions?

- Planning/policy/regulatory/legal issues (including international)
- Public perceptions about sub-surface activities.
- Natural capital and valuation
- Water (use, supply, contamination – e.g. solvents for hydraulic fracturing)
- Seismicity
- Ecological impacts
- Health impacts
- Characterisation of sub-surface environments
- Need to have scalable pilot projects in order to investigate impacts.
- Uses for CO_2(speciality chemical etc)

What challenges will we face? Where are the shortfalls?

- Characterisation and communication of risks and hazards
- Establishing the right level and scale of monitoring coupled with innovation in monitoring techniques
- Bringing the public and communities (including scientific) along
- Monetary and non-monetary metrics for evaluation
- Appropriate monitoring for seismicity, air, geology etc
- Intellectual property
- The policy priority attached to impact studies

What might / should we do to make ourselves 'match-fit'?

PhD training? Research Infrastructure / underlying facilities? Funding philosophy?

- Disciplines needed: chemistry, physics, biology, geology, economists, planning, other social sciences, modelling, simulation, high-performance computing
- Interdisciplinarity is important
- Skills need to be transferrable
- Academic linkages with industry and investors (doing & thinking)
- Capacity for field trials
- Public engagement (Research Councils) as part of the "doing"
- Coherence across the supply chain.
- Coherence across funders – TSB, ETI, DECC, Defra, Research Councils, industry)

- Curation and accessibility of data (two types of data held by BGS: a) that collected with public funding (accessible); b) that developed with the private sector (not easily accessible)

10.4 Group T: Training

General needs

- Flexible MSc courses providing the human resources needed for CCS are needed, but also need rigorous courses that establish basic geological and fossil-fuel skills
- Centres for Doctoral Training constitute a good model, but also need standard discipline-based PhDs

What challenges will we face?

- Reliance on foreign students for MSc courses who may not be able to continue into employment in the UK
- Don't always attract the best students as there's a continuing uncertainty in CCS deployment. May be less attractive than renewables?
- Balance between acquiring deep skills and wider transferrable skills.
- Geothermal needs very similar skills to oil and gas
- Trade-offs have not yet been made between research and training

Where are the shortfalls?

- Shortfall of science and engineering graduates relative to UK needs.
- Private industry won't or can't fund all training needs. Who in the public sector is responsible?
- Little funding for project students them.
- Problem of transition from post docs to permanent academic posts

What might / should we do to make ourselves 'match-fit'

- Less graduates going into the City!
- Continue process of consultation through initiatives such as the Energy Strategy Fellowship
- Ensure that UK CDTs are world leading and value-for-money
- Ensure that the world-leading standard of our Masters courses are recognised
- Do more reach-out events to schools about energy
- Gather data on doctoral and masters programmes in order to identify the current state of the area, including numbers and types of students and specific strategic shortfalls
- Need training to facilitate transfer of skills

PhD training? Research Infrastructure / underlying facilities? Funding philosophy?

- Large pilot-scale facilities tied to research and training groups
- Shared UK community facilities and infrastructure
- A broader dialogue on who funds what - RCs, government departments, and industry
- UK PhD and MSc Encourage international students to follow 4-year CDT-style training instead of 3-year projects
- Improve career path for post docs
- UK MSc and PhD programmes are world leading and the Research councils should advertise this to the UK government

10.5 Community X: Technology development and users

General

- This group covers: technology developers; technology users; project developers; and service providers
- The group highlighted the need to develop the next generation and future generations of technologies, looking at a multi timescale horizon
- The group focused on the timescale out to the 2020s, roughly ten years ahead and hence considered mainly short-term fixes and the medium term success of technologies. "How to get things on the ground to get learning by doing for industry and academia"
- The group focused on: near-term fossil fuels; biomass; and CCS technology development
- Important to maximise existing resources, whilst reducing the major costs involved in technology development and deployment
- The country will increasingly rely on clusters in the future

What are the most important fossil fuel/CCS applications for your community?

- Fossil fuel and biomass
- Power generation
- Process industries: – petrochemical, steel, cement and refineries
- CCS technologies included solvents, compression and structural materials

What are the key research questions?

Near term (10 years ahead, early 2020s)

- Key over-arching question is the extent to which technologies represent deployable systems
- Addressing the mismatch between supply and demand by improving plant maintenance, flexibility and energy storage facilities
- Addressing RAMO (reliability, availability, maintainability & operationality) issues
- Health and safety issues
- Reducing technology costs
- Understanding the learning curve and how this influences the cost-effectiveness and optimisation of technologies
- The value propositions associated with technologies and how these might be packaged to gain competitive edge

Medium term (2025-30)

- Next generation capture
- CO2 utilisation
- Energy penalty reduction
- Fuel flexibility
- Clustering
- Scalability
- New build/retrofit
- Energy storage with energy conversion

What challenges will we face? Where are the shortfalls?

- Funding/investment and appropriate capabilities/capacities (see below)
- Technology choice and diversity
- The risks associated with new technologies, e.g. first mover disadvantage
- Public perception and acceptance of new technologies
- Infrastructure constraints – planning, regulatory
- Reliability across the CCS chain
- Regulators who understand technologies and their application
- Trained personnel

What might/should we do to make ourselves 'match-fit'?

- Connectivity across all relevant stakeholders
- A consistent vision of the future
- Ensure that skills attained via research degrees remain relevant even if the industry radically changes
- Develop international collaborations to promote cross-country support
- Highlighted the requirements for signals and drivers, notably policy, regulatory and technology based drivers to deliver the right thing(sets of technologies) at the right time frame
- Technology roadmaps and common agree frameworks
- Knowledge transfer
- Coherence across the TRLs, Research Councils, TSB etc
- Grid connections available – power, transport, storage
- Accessible, well-funded facilities

PhD training? Research Infrastructure / underlying facilities? Funding philosophy?

- Not only PhD training but also more industrial/professional training e.g. apprenticeships.
- A range of academic qualifications, e.g. Masters, EngDocs, not just PhDs
- Need to not just 'skill-up' our workforce but ensure we retain them once they are
- National centres to develop relevant skills, especially to help development of SMEs.
- Need for a skilled workforce, which included not only academic skills (e.g. theory of application, PhDs) but also professional/industry type skills (e.g. process of application, CPDs etc).
- Research Council need to be able to shape capabilities. And they have been reasonably successful in certain areas, e.g. CCS and conventional generation
- Shared facilities will help, but they require a degree of trust, knowledge transfer and connectivity across the chain
- Virtual simulation
- National Test Centre(rapid testing, prototyping)
- Necessary grid connections and broader infrastructure (e.g. carbon transport and storage)
- Drivers to support technological development (e.g. policy, planning, market signals, technology roadmaps)
- Support services (consultancy, legal) to help firms engaging in technology development
- Information resources available for microenterprises and SMEs to help them move towards operational businesses

11 Research and Training Needs: A Deep-dive in Areas of Application

Following the 'horizontal' communities split of the research hot-spot analysis exercise, the attendees self-organised themselves into five groups, each representing an 'application' of research to solve a specific problem or set of problems (Table 8). These application areas were:

Group Number	Application Area
1	Capture Processes
2	Geothermal Energy
3	Subsurface Reservoir Performance
4	Transport + Infrastructure
5	Storage

Table 8 Groups for deep-dive into different areas of fossil fuels & CCS application

Attendees were then asked to analyse the application areas using a set of structured questions, in a similar manner to the communities hot-spot exercise. These questions were:

1. *What are the most important research questions in this area of application?*
2. *Which research communities need to contribute?*
3. *What challenges will we face and what shortfalls will we encounter?*
4. *What might / should we do to make ourselves 'match-fit' for the future, including resource, infrastructure and training needs.*

	Key Research Questions	*Research Communities*	*Challenges & Shortfalls*	*Match fitness & resource needs*
Group 1 – Carbon Capture	• Effect of small impurities from capture processes on storage/transport • What do you have to do to get the impurity levels done? • What are the knowledge gaps? Impurity effects on reservoirs	• Needs a multidisciplinary approach • Chemical • Materials • Mechanical • Fluid Mechanics • Civil • Environmental • Systems • Control • Process Engineering	• Under-represented communities: Economists, Insurers, Banks. Big project management. Need engagement from technical community with these communities. • How can you reduce costs and risk of big projects? • How can you deal with intermittency?	• CPD training is important for developing a skilled workforce. Not covered previously • Sandwich training • Train generalists as well as specialists that are "socially" aware of public perception issues • Shared facilities/infrastructure for training. • Funding philosophy - Funding for research programmes or for projects? • Field trials and studies important.
Group 2: Geothermal	• Future research could analyse the permeability of the UK's landscape in areas of abundant geothermal energy via 3D simulation. • Examine methods to improve this level of permeability to increase fluvial flow. • Need to understand the extent to which these processes may degrade water quality. • How much heat can we sustainably extract before there is a reduction in flow? Need to understand issues around heat abstraction optimisation & planning. • A focus on potentially negative environmental issues, concerns around subsidence, microseismic events and water depletion via geothermal energy extraction.	• Geological & earth sciences • Engineering (also civil engineers, reservoir engineers, CHP, energy from waste) • Chemists • Environmental scientists • Planners • Environmental regulators • Business studies •	• Joined up thinking • Low value of hot water compared to say oil – 'Barrel of water costs nothing compared to a barrel of oil' • Heat of considered to be a pollutant rather than a resource • Potential acceptance issues e.g. earthquakes from geothermal energy extraction in Basle, Switzerland • Lack of knowledge in this area, with little research having been done since the 1980s • Lack of young blood in this field, with a number of experts close to retirement with no new generation coming through • Policy, planning and regulation issues around geothermal energy	• Need to drill more explorative boreholes • Need to use existing boreholes more effectively, e.g. those used for oil & gas or mineral deposits. These may be used to collect relevant data around geothermal energy in certain geographical locations 'piggy-backing' • PhD training needs – not enough PhD students working on this topic. Need to join up the generations! This may to some extent be addressed by BriGeothermal, a virtual research institute involving Durham, BGS, Glasgow & Newcastle • Need to utilise knowledge from gas-fired district heat systems to help develop geothermal energy systems (i.e. distribution, supply etc). Opportunities for provision are mainly for new build but also

	• Need to explore issues around regulation of geothermal water extraction and licenses. • Greater research is needed into the methods for harnessing geothermal energy for heat and electricity generation, and issues around the deployment of heat networks. • How can existing void spaces (e.g. mines) be used to access low level geothermal heat? • May be a need to improve heat exchange technologies.			potentially some retrofit opportunities.
Group 3: Subsurface Reservoir Performance	• Understand earth materials properties in novel matrices. • Composition of produced gas/oil. • Long-term behaviour of well and facilities construction materials (steel/cement etc). • Keeping stored CO2 down there. • Long-term disruptive sources e.g hydrates.	• Subsurface/Geo-mechanics • materials science • Chemical/mechanical • engineering • Environmental impact science, • Economics • Social/press officers. • Capacity and training community. • Petroleum engineering.	• How do we ensure surface/eco impacts are sustainable? • Socio-economic/public perception issues. • Economics of extraction. • Improved communication with public/media.	• More training in geo-mechanics, material science, petroleum engineering. • Pilot and fund field studies. • Work to establish environmental baseline. • Need to fund large facilities e.g diamond and Isis. • Training in geophysics.
Group 4: Transport and Systems	• Scalability and understanding constraints (e.g. CO2 quality/impurity) • Optimisation problems in order to understand options better. • What needs to be done to avoid costs being prohibitive? • The implications of moving to a larger and distributed network – these are huge (much harder to control constraints/operating parameters, flexibility) • What geographic (and technical) coverage are you trying to	• Regulators, certification, insurance etc • Environmental – assessment of impact of leaks, also changes linked with normal operation (e.g. potential heat transfer out of CO2 pipe may heat the soil around it affecting crops) • Control and instrumentation • Electrical power networks	• Getting people from different disciplines to talk. • Moving up through different scales of projects. • Complexity – so many factors • Reducing uncertainties in constraints (how easy to control?, what can go wrong and how quickly?) • Ownership of sites/CCS project components – how might this make things easier/more difficult for getting integrated thinking deployed? • A lack of practical experience is	• Large-scale consortium projects that are targeted and managed, including relevant stakeholders. • Significant industry/stakeholder involvement in reviewing applications (outside normal academic peer review process where there is a significant chance that reviewers that do not understand the proposal are having a significant impact on funding decisions) • Spadeadam as a national resource? (Site where a lot of the

	integrate over? • need to look at developing international standards and guidance to ensure international consistency. • Metering that is good enough for fiscal purposes is important and needs some underpinning science/engineering to be done.		some parts of the community.	experimental work to understand CO2 release from pipelines has been undertaken in recent years.)
Group 5: Storage	• Engineering of modern boreholes/borehole integrity. • Baggage of chemistry from capture – impurities in gas affects reservoir injectivity. • Near field (i.e near well = transient effects • Understanding flow in aquifers. • Understanding reservoirs in detail - Water/Co2 saturated water acting as a buffer may be a good or a bad thing. • Main field (outwith well): dissolution; reactivity; = physical consequences (e.g. buoyancy) • Mechanical damage to natural seals. • Leakage through legacy boreholes (containment integrity).	• Geo-scientists; geo-engineers; petroleum engineers (fluids and pipes); software engineers; hydro-geologists. • Tool designers – experimental physics people. • Environmental impact at the surface. • Links to capture/transport people – what's coming down the pipeline? • Policy/legal/regulatory /public engagement.	• Legal regime – may place impossible scientific demands e.g. 99% probability of no leaks. • Need a management plan for how to remedy problems/leaks. • How do you detect leakage from point sources? • Nobody has worked on overburden containment = above the seal. This is legally part of the storage regime.	• Need new modelling and modelling tools for prediction - Handover to government depends on modelling/modelling verification leading to 10,000 year prediction. • New generation of tools to predict where CO2 is initially in the storage site.

12 Plenary Discussion

12.1 Group 1 - Capture

- A significant proportion of the discussion is internal capture application discussion so not reported back to plenary. Wider issues that are of broader relevance include the impact of impurities and also full system integration (e.g. who deals with non-constancy of CO_2 flow in the system – do you add buffer storage at the capture end of the CCS change or just deal with intermittent flow in the rest of the system?)
- Communities to contribute – large list of technology areas (most already somewhat engaged), communicators of technology do need to make progress with getting in touch with non-technical folk including insurers and the bank though
- Training – need everything. Deep dive specialists and also populate technology environment with good generalists, projects are hugely complex (potentially international) so also need expanded project management skills etc

12.2 Group 2 – Geothermal

- Permeability landscape needs to be mapped and understood. Cross-cutting technologies/stimulation etc involved so need to look at what can we learn from others.
- Various technical opportunities and threats (and learn from things that have gone wrong with other unconventional stuff)
- Need to have planners as well as 'usual suspects' involved
- Challenges include needing more joined up thinking. For use in the 'real world' also have the issue that geothermal is low value energy and that heat can be thought of a pollutant as well as a resource
- Need not just individual projects with relatively short (approx. 3 year) timescales – needs to be much more joined up, currently working on getting a joined up research community going in this area though (Durham, BGS, Glasgow and Newcastle as an initial core group)

12.3 Group 3 - Hydrocarbons (unconventional and conventional oil and gas)

- Revisited some stuff from subsurface group
- Then extra stuff discussed in this group included looking more at earth materials (not just rock, but also stuff you put in to the rock). Key issues include long term integrity of wells, cements etc and dealing high pressure/temperature. There is a broad range of disciplines needed here
- Surface impacts are also important – need to keep what you have in the subsurface still down in the subsurface (i.e. integrity is key). Have to understand the overburden (the rock above the part of the subsurface that you are actually using), fracture propagation, ecology and environmental science etc
- Baseline data plays a particularly important role here. Field studies are essential and probably need to go beyond a very small number of pilot sites
- Economy of various types including public perception is also key. For example, the unconventional extraction industry is doing public perception/engagement/education
- Finally, note that when shale gas and CBM (coal bed methane), gas hydrates, UCG and other applications actually happen in reality is time dependent. Shale gas and CBM could be perhaps 20-30 years ahead

12.4 Group 4 - Systems and Transport

- Ended up very high level (whole CCS system and a bit broader scope beyond that) “in orbit, not just in a helicopter”
- How to get system to work to get international integrated projects going? Operability, flexibility etc. Failure cases, upset conditions – how to deal with those and mitigate them (risk/failure), also getting redundancy in system (but not too much redundancy)
- Communities needed are pretty much anyone and everyone
- Then jump to point 6 – complexity is hard, so then really need a national mission to get industry/academia/Gov/regulators etc working together at the breadth and depth required

12.5 Group 5 – Storage

- Growing list of things involved in this area
- Issues related to what comes down the pipeline chemically (extreme case would be raw flue gas), large flow rates in well (stress, legacy issues -> initial stress field too) so have near well and then further away dissolution of CO2 into water and other issues related to flow management in the reservoir (delivering what we want). Issues relating to monitoring and verification (what will be changing that can actually be monitored cost effectively), issues for public confidence building.

  Everyone in the system has to have some involvement in what happens at the end of it – scientists, policy also software developers etc. Where to go with infrastructure and facilities – predicative models need data, field scale pilots are essential. Regulatory framework needs input from real experience too
- Lots of CCS here – perhaps partly because most heavily funded in recent years?

13 Reflecting on the Workshop

Christine Bell chaired a Radio Scotland “phone-in” where participants put questions to a panel comprising Jon Gibbins, Aidan Rhodes, Jim Skea and Mike Stephenson.

Q: What has been most useful about having this group of experts together in one place?

A major advantage has been the ability to avoid silo effects and make connections: across skill sets; bringing the NERC and ESPRC communities together; interdisciplinarity, especially in relation to subsurface issues; and between technologists and economists. Links between academia and industry were important, including the potential for spin-outs. However, one panel member thought that there had been poor mixing of participants during some group work.

We needed a good pipeline of engineers and others over the next 30-40 years. Continuity is needed with this time horizon in mind.

The workshop had identified the risk that fossil fuel and CCS could fall between the cracks across NERC and EPSRC. More speculative research challenges had not been covered and there was a risk that blue sky ideas could slip out of the portfolio. More speculative things such UCG or synthetic biology should not be lost. While they may not merit a large resource allocation, they should not fall off the radar completely.

Subsurface management has come up as a key theme. The subsurface has multiple uses. Public concerns may be alleviated if the subsurface is seen to be managed openly.

Other key messages were that: there needs to be continuity of support and training across all disciplines; there is still a mismatch between the size of the problem (CO2 emissions from fossil fuels) and the level of available funding.

Q: How will the Strategy Fellowship deal with research topics that lie at the interface between different workshops, e.g. between fossil and biomass in petrochemicals or power generation?

Relevant messages from this workshop will be communicated to subsequent workshops. Linkages will be reflected in top level documents. The Fellowship team will consider developing an additional report that focuses exclusively on connections.

Q How will the areas of science relevant to sub-surface management be linked?

Different scientific disciplines cut across different topics such as carbon storage, UCG, unconventional gas etc. This is a major message form the workshop that will be communicated in the final report. Subsurface management could be used as a focal point for the report allowing different bits of science to be linked.

However, there is a difference between simply being aware of on-going activities in other areas, and overlaps the same science is being used in applications not covered by this workshop. The differences in the way these overlaps need to looked at and worked out. These two types of overlap need to be addressed differently.

Q. Can you summarise in a single phrase the message from the two days?

> There is a rejuvenation of the topic of fossil fuels in the overall energy research agenda. Since RCUK established a cross-council energy programme nearly ten years ago, the topic of fossil fuels has been considered "old energy" and has not been prioritised. This is no longer the case.
>
> The research end of things is doing quite well. The challenge is how we take the research to impact, given uncertainty in energy policy. While the research field has changed, has the application field changed to the same extent?
>
> Finally, it was noted that one of the companies represented at the workshop had five 5 key asset categories in the hydrocarbon area and that a resurgence in technology and science was opening up new business areas.

14 What Should the Research Councils Support?

This exercise asked participants to record what they felt the Research Councils should **start** doing to assist the fossil fuel and CCS community, what they should **continue** to do, and what they should **stop** doing or do less. Participants recorded their thoughts on post-it notes, arranged by category.

14.1 Start

- Identify value pathways to impact & partners to deliver impact before calls.
- Co-ordinate with other funding groups e.g DECC/BIS/TSB
- Talk across silos: Fossil energy/CCS/renewables/nuclear
- Bigger pots of money for longer field trials/pilots
- Fund Masters courses
- Start having stronger focuses on the environment, ground water, seismicity, fugitive emissions
- Start a large, long fossil fuel + storage + heat programme
- Cross Research Council projects + buy into major pilot programmes
- Start to map out the range of PhD training that is happening in the CCS and fossil fuels field
- Look at research as part of a wider RDD&D landscape, with a 'value-chain' approach and more joined-up funding mechanisms
- More full system analyses
- Start allowing larger funded consortia to bid for extra funding to allow collaboration.
- Start prioritising and clarifying the research road map
- More joint funding by EPSRC, TSB, ETI etc for applied research
- More full system analyses
- More 'oil + gas' research
- Start allowing PhD students to be funded on grants
- Start refunding MSc training

14.2 Continue

- Continue and expand focus on research hubs
- Continue MSc funding and PhD funding on grants
- Continue a sustained long-term funding structure and vision
- Continue interdisciplinary consultation
- Continue to consult
- Incentivising impacts
- Continue postgraduate training
- Thematic programmes
- Continue funding world-class research and training
- Continue developing research groups and research communities

14.3 Stop

- Do less environmental impact funding
- Stop separating NERC and EPSRC in this sector.
- Stop obsessing about the NERC and EPSRC boundary
- Stop doing things where we are not making an impact – focus on things we do well.
- Do less atmospheric science.

- Do less environmental impact work.
- Stop funding nuclear fission
- Stop making significant decisions without consultation.
- Improve the review of proposals for funding. Panels can be very partisan.
- Stop penalising multidisciplinary proposals/research.
- Stop drilling Antarctic lakes with no backup science output.

14.4 Conclusions

Several main themes are apparent from the lists. The first is an emphasis on skills and training – many of the entries in the '*start*' list mention funding from the Research Councils for MSc students and PhD students on research grants. Another repeated sentiment in the '*start*' list is the need for funding for larger research consortia and the need for more interdisciplinary consortia to be formed, connecting up the 'silos' of research that often operate separately. Full-system analyses, investigating how skillsets, problems and infrastructure could interoperate across these 'silos', was stated as important by several attendees. Greater funding for larger projects that extend into field trials and pilot projects are also seen as important, with larger 'hub' projects and programmes and more inter-linkages with industry and bodies higher up the innovation chain. It was also suggested that previously-formed consortia should be allowed to bid for extra funding to allow and extend collaboration efforts. Mapping and planning the research landscape and future efforts was also identified as a priority, understanding value-chains and joined-up research funding.

Attendees thought the Research Councils should '*continue*' several of the same things they were identified as needing to '*start*', including expanding their focus on research hubs and interdisciplinary collaborations. MSc and PhD funding and grants was again identified as something the Research councils needed to continue in order to train new talent, and there were several attendees who were interested in seeing the Research Councils continue and expand their consultation efforts. Common themes in this area involved ensuring that the UK's research groups were well developed and that the UK continued to ensure that it was training another generation of fossil fuel and CCS experts.

For the '*stop*' section, there were several responses asking that EPSRC and NERC stopped rigorously enforcing boundaries between their funded research, as projects in this sector often crossed boundaries and were not able to be characterised purely as an EPSRC or NERC project. This was viewed as penalising multidisciplinary research. There was a desire to stop spending resource on areas where the UK is viewed as not doing well and to focus on our perceived strengths, as well as to improve the review of proposals for funding, some review panels being identified, rightly or wrongly, as partisan. Several attendees wanted to see less environmental impact work, possibly feeling it slows down the pace of demonstration and deployment. Atmospheric science and nuclear fission were also identified by participants, but are outside the scope of this workshop.

15 Research Capabilities: Meeting Future Challenges

Working individually, people were asked to where they we are now in terms of research capabilities for tackling *future* energy challenges. They were invited to score these on a scale of 0-10 (0 = no chance, 10 = well setup) and explain their score on a post-it note. The following graph shows the distribution of issues raised on 21post-its (some of which made multiple points). The average score was 4.8 +/- 2.3. The following three tables, dividing the results into three classes: high capability (7-10), medium capability (4-6)and low capability (0-3), and set out the detailed results. Most of the responses focused on capabilities at a generic level rather than in relation to specific technologies. There was more divergence of view than was the case for capabilities to meet current needs, though this partly reflected a glass half-full/half-empty perspective on funding prospects. Many responses asserted that research goals could not be achieved without additional funding for both research and training (Figure 3Figure 3 & Table 9).

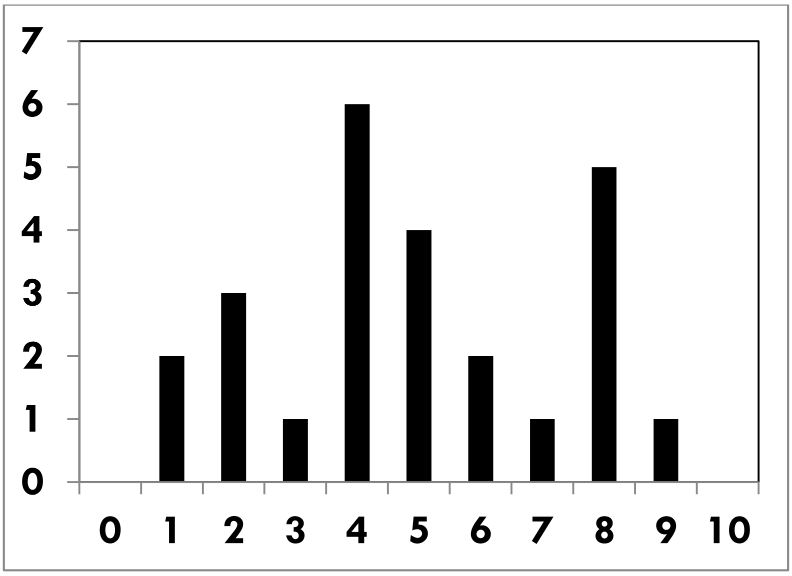

Figure 3 Distribution of perceived UK capability levels

High capability levels			
7	8	9	10
Research infrastructure is in place, expertise (?) here if sustained support is available	High capability if there is a supporting environment	UK has most of the skills but is fragmented, under-coordinated and under-funded	-
	Just get on and do it		
	Strong on consultation		
	World class science		
	Renewed focus on oil and gas		

Medium capability levels		
4	5	6
Skills exist, but integration and awareness of the need to apply them is not developed	CCS: great opportunity to lead but need big pilot to underpin progress	Skills/PhD training need to ramp up
Research linkages are being identified, but will they be funded?	We have the core expertise but not the infrastructure/ investment for application	Fundamental skills exist but prioritisation and direction needed
We (probably) have the research capability but need policy and investment to drive change	Lots of potential, but risk of not getting a) industry/user input; b) Research Council funding	
More progress needed in identifying key challenges and organising to meet them. Still fragmentation.	Public perception/community buy-in issues need addressed. Use new social media.	
Lack of future training, funding and government policy		
This workshop has burst the		

silos. Outside people are still "in-silo". We are still not set up for the new view on fossil fuels		

Low capability levels			
0	**1**	**2**	**3**
	Legacy of CCS/renewables focus	Lack of funding for large scale projects	Without additional funding won't be able to tackle the research remit
	No funding for training	Trivial funding	
		Many experienced researchers are 55+. Future skills gaps	

Table 9 UK's current levels of research capabilities across the energy sector

Annex A: Agenda

Tuesday 8th January	
10.15	Arrivals and Registration
10.30	**Session One: Introduction** Introduction to the purpose of the event and the process of the event and feedback on the previous workshops
	Discussion and Activities to share current thinking in this area of research and generate different perspectives and ideas
13.00	Lunch
14.00	**Session Two: Exploring the Research Themes** Discussions and activities to identify and develop potential research hot spots and to explore these with different perspectives
	Session Three: Reflection and Summary Activities to reflect on the emerging themes
17.30	Close
19.00	Drinks Reception and Dinner
Tuesday 9th October	
9.00	**Session One: Introduction to Day Two**
	Session Two: Prioritisation and Analysis Discussions and activities to explore what the deeper research challenges and the enablers needed for this process
12.30	Lunch
13.30	**Session Three: Further Development of Research Themes** Discussion and activities to focus on the themes that are starting to emerge that interest you and to probe these ideas further.
	Session Four: Summary of the discussions/Moving Forwards Draft executive summary of the workshop output with opportunities for debate and clarification of issues and identification of the overall actions needed
16.00	**Event Finishes**

There will be short refreshments breaks at appropriate times in the morning and afternoon sessions

Annex B: List of Attendees

Surname	Forename(s)	Organisation
Allison	Brian	DECC
Bell	Christine	Centre for Facilitation Services
Brennan	Fergal	Cranfield University
Busby	Jon	British Geological Survey
Chapman	Nigel	Centre for Facilitation Services
Drage	Trevor	University of Nottingham
Francis	Rob	University of Cardiff
Franklin	Chris	NERC
Garett	Steve	Chevron/Petroleum Exploration Soc.
Gibbins	Jon	University of Edinburgh
Gluyas	Jon	University of Durham
Green	Chris	G Frac Technologies Limited
Hannon	Matthew	The Fellowship Team
Haszeldine	Stuart	University of Edinburgh
Irons	Robin	E.ON UK
Kammerer	Iris	The Fellowship Team
Krevor	Sam	Imperial College London
Macatangay	Rafael (Manny)	University of Dundee
MacKay	Eric	Heriot-Watt University
Pourkashanian	Mohamed	University of Leeds
Rhodes	Aidan	The Fellowship Team
Roddy	Dermot	University of Newcastle
Sharman	Philip	Evenlode Associates
Skea	Jim	The Fellowship Team
Snape	Colin	University of Nottingham
Stephenson	Mike	British Geological Survey
Taylor	Kevin	University of Manchester
Thomson	Rachel	University of Loughborough
Williams	Jacqui	EPSRC
Williams	Paul	University of Leeds
Wright	Joanna	Keele University
Yardley	Bruce	University of Leeds